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INTRODUCTION

Remotely Operated Underwater Vehicles (ROV's) sometimes must attach themselves to an underwater structure in order to inspect, clean or repair the structure with manipulators and other tools. Control of the vehicle and/or the manipulator while the vehicle is constrained by the attachment mechanism is difficult with classical control systems. Typically very high forces and possible destruction of the manipulator can result if the control system and the constraining attachment system interact with one another. A general technique called impedance control has been developed to deal with control problems for manipulator systems subject to unknown or variable external loads, without causing excessive forces or self-destruction. This concept has been extended in the work described here to include constraints as a special kind of external load. Thus, it is shown that the controller can be built to work safely with systems having constraints or attachment mechanisms which severely limit motion.

ABSTRACT

This report presents a method for wide bandwidth stiff position control of unmanned underwater and space vehicles. This begins with an argument that the use of feedback alone may not provide an underwater or a space vehicle sufficient bandwidth with large stiffness. In other words, with feedback alone the vehicle may not behave like a stiff platform in the presence of a wide frequency range of disturbances. Given this limitation, we suggest that the vehicle must be connected to environmental structures by means of cables or grabbers. These connecting cables will develop dynamic and kinematic constraints on the vehicle motion. This problem led to the development of a method that allows for control of the motion of constrained underwater or space vehicles. This method is called "impedance control" (1), (2), (3). The frequency domain essentials of impedance control and a robust controller design method are given in reference (3). We explain how, with the help of this method, a vehicle connected to a structure by means of cables can be positioned with high stiffness while at the same time the cable tensions are also under control.

Problem Statement

Many deep underwater operations are done by manned or remotely operated vehicles equipped with manipulators. Because of the large inertia of these vehicles (relative to the manipulators' inertia) and their inability to move in some directions, it is not trivial to maneuver these vehicles during a manipulative task. In performing a task (e.g., opening a valve), it is often preferable to keep the vehicle as a stable platform and maneuver the manipulator.

An underwater vehicle is always subject to external forces resulting from water motion, manipulator reactions and power/communications tethers. These forces on the vehicle act over a wide frequency range (e.g., from low frequency water currents to high frequency motion of the manipulator.) Rejection of all disturbances on the vehicle and maintenance of the position and orientation of the vehicle over a wide frequency range of the operation by feedback is not trivial. This is true because uncertainties in the model (e.g., hydraulic actuator system) will assign an upper bound for the bandwidth of the compensated loop transfer function. In other words, a designer is always faced with certain performance trade-offs; these involve command-following and external-load rejection versus stability robustness to high-frequency unmodelled dynamics. The conflict between these two sets of objectives is evident in most positioning systems.

Low-frequency disturbances on the vehicle can be rejected by feedback, and high frequency disturbances do not affect the vehicle motion. On the other hand, there exist disturbances with a frequency range of operation too large to be compensated by feedback, but small enough to affect the vehicle's motion. This frequency range is near the cross-over frequency of the compensated loop transfer function. In other words, when most of a vehicle's disturbances that are deep inside of the bandwidth of

the compensated open-loop can be rejected by feedback, disturbances that are far outside of the bandwidth cannot affect the vehicle motion. But the disturbances that lie between these two frequency ranges can affect the vehicle motion. (An analogy can be observed in airplanes: Passengers always feel some disturbances. These disturbances act over a frequency range that cannot be compensated completely by feedback.)

The Proposed Solution

To overcome this problem, the vehicle can be connected to the structure by cables. Grabbing on to an external structure can also be done by the manipulator on the vehicle. The cables' end-points can be equipped with magnets, suckers or hooks, and the cables can be tensioned by using the vehicle's thrusters in the necessary direction. Figure 1 shows this arrangement. Maintaining the tension of the cables between the structure and the vehicle will give the vehicle more definite position and orientation. If the cables are stiff, their dynamics may overcome the vehicle's inertia for some bounded frequency range. The stiffness of the cables will dominate the dynamics of the system of the vehicle and the cables over a wide frequency range. This frequency range can be approximated by $\sqrt{\text{cable stiffness/vehicle inertia}}$. Throughout this frequency range, the system consisting of the vehicle and its cables behave like a very stiff spring, and external loads in this frequency range do not affect the vehicle position. The above procedure for positioning the vehicle implies the existence of significant interaction forces between the vehicle and its environment via the cables. The cables impose dynamic constraints on the vehicle's motion. In any mission it is desirable to control the position and orientation of the vehicle and the tension of the cables, even though the number of cables and the locations of their attachments to the structure

may not by known in advance. Here we can see the need of a control technique for this type of constrained maneuvering in which the existence and general character of the constraint is certain, but the exact nature of the dynamics and geometry of the constraint is not known in advance.
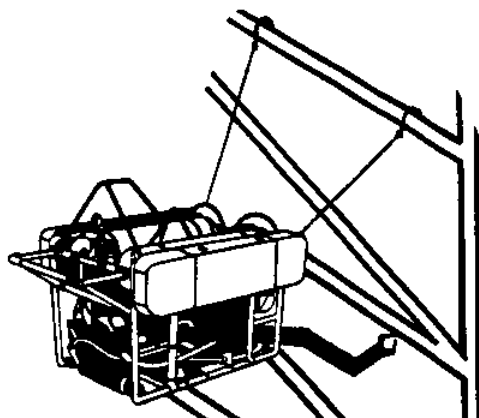

Figure 1: Underwater Vehicle Connected to Structures

In the next section we present a control technique for positioning a vehicle in its allowable space and simultaneously controlling the forces in the cables. This method is called Impedance Control [1],[2],[3].

Impedance Control [3]

In traditional controller-design methodology, external-load rejection is an important consequence of the design method. This property is useful as long as the vehicle is unconstrained. Once the vehicle is constrained, the compensator treats the forces of interaction with the environment as disturbances and tries to reject them, thus causing greater interaction forces. Saturation, instability and physical failure can be the consequences of this type of interaction. Thus in many applications such external forces should be accommodated rather than resisted.

An alternative to external-load rejection arises if it is possible to specify the interaction forces generated in response to imposed motion [3]. The design objective is to provide a stabilizing dynamic compensator for the vehicle such that the ratio of the motion of the closed-loop system to an interaction force is a desired constant within a given operating frequency range. The above statement can be mathematically expressed by equation 1.

$$\Delta D(j\omega) = K \Delta Y(j\omega) \quad \text{for all} \quad 0 < \omega < \omega_0 \tag{1}$$

$\Delta D(j\omega)$ = n×1 vector of deviation of the interaction load (forces and torques) from the equilibrium value in the global coordinate frame.

$\Delta Y(j\omega)$ = n×1 vector of deviation of the interaction-port position and orientation from an equilibrium point in the global coordinate frame.

K = n×1 real-valued non-singular stiffness matrix with constant members.

j = complex number notation $j^2 = -1$

The stiffness matrix is the designer's choice, and in general it contains different values for each direction. By specifying K, the designer determines the behavior of the system in constrained maneuvers. Large members of the K-matrix imply large interaction forces and torques. Small members of the K-matrix allow a considerable motion of the system to interaction forces and torques. Stiffness values in one sense represent the type of behavior a designer may wish a stable positioning system to exhibit. For example, if the system is expected to encounter some physical constraint in a particular direction, a stiffness

value must be selected such that the desired contact force is ensured in that direction. In directions in which the system is not likely to meet any physical constrains, a stiffness value with a proper position set-point must be selected such that the system follows the desired reference inputs. Even though a diagonal stiffness matrix is appealing for the purpose of static uncoupling, the K-matrix is not restricted to any structure at this stage. Selection of the K-matrix is considered as the first item of the set of performance specifications.

Mechanical systems are not generally responsive to external loads at high frequencies. As the frequency increases the effect of the feedback disappears gradually, depending on the type of controller used, until the inertia of the system dominates its overall motion. Therefore, depending on the type of system, equation 1 may not hold for a wide frequency range. It is necessary to consider the specifications of ω_o as the second item of the set of performance specifications. In other words, two independent issues are addressed by equation 1 : first a simple relationship between $\Delta D(j\omega)$ and $\Delta D(j\omega)$; second, the frequency range of operation, ω_o such that equation 1 holds true.

Besides choosing an appropriate stiffness matrix, K, and a viable ω_o, a designer must also guarantee the stability of the closed-loop system. Therefore, stability is considered to be the third item of performance specifications.

The achievement of the set of performance specifications is not trivial; the stiffness of the system cannot be shaped arbitrarily over an arbitrary frequency range. A designer must accept a certain trade-off between performance specifications and stability robustness to model uncertainties. The conflict between the performance specifications and stability robustness specifications is evident in most closed-loop control systems. The sets of performance specifications and stability robustness specifications taken together establish a complete set of

controller design specifications. Figure 2 shows how this set is categorized [3].

```
                                           ┌   Stiffness Matrix, K
                                           │
                          ┌  Performance    │   Frequency range of
                          │  Specifications─┤   operation, ω_o
                          │                 │
      Controller         │                 │   Closed-loop
      design ────────────┤                 └   Stability
      Specificatins       │
                          │
                          │  Stability
                          └  Robustness
                             Specifications
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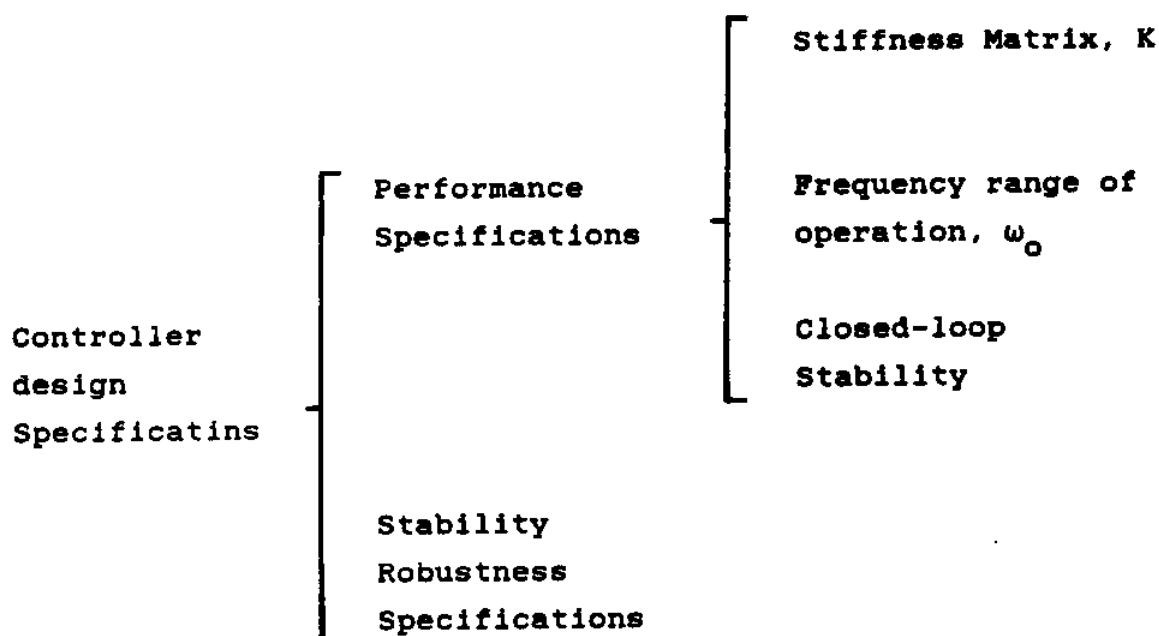
Figure 2: Controller Design Specifications

We are looking for a mathematical model that will enable us to parameterize the three items of the set of performance specifications. The parameterization must allow the designer to specify the stiffness matrix, K, and the frequency range of operation , ω_o, independently, while guaranteeing stability. All such performance specifications can be mathematically expressed by equation 2.

$$(J\ s^2 + C\ s + K\ )\ \Delta x(s) = \Delta D(s) \qquad s=j\omega \qquad (2)$$

K, C and J are nxn real-valued non-singular matrices. Note that it is still necessary to achieve equation 2 for all $0<\omega<\omega_o$. Proper selection of the K-matrix allows the designer to express the desired stiffness, while judicious choice of the

inertia matrix, J, and the damping matrix, C, assures the achievement of ω_o and stability of the system.

To clarify the contribution of J, C and K, consider Figure 3, the plot of the $\Delta x(j\omega)/\Delta D(j\omega)$ from equation 2 when n=1 and the system is slightly underdamped. $\Delta x(j\omega)/\Delta D(j\omega)$ remains very close to 1/K for some bounded frequency range. In other words, the plot of $\Delta x(j\omega)/\Delta D(j\omega)$ approximately exhibits the relationship in equation 1 for some bounded frequency range. Therefore K in equation 2 parameterizes the first item of the set of performance specifications. If K is given, then ω_o and the stability of the system depend on J and C. In other words, a designer can change either J or C to affect ω_o and the stability of the system. For example, for a given K and C, decreasing J causes the corner frequency , K/J and consequently, ω_o to increase. Changing J also moves the eigenvalues of the system. For a given positive set of K and C, a negative J locates one eigenvalue in the right half plane, while a positive J guarantees that both eigenvalues always stay in the right half complex plane. The dependence of the ω_o and the stability of the system on C can be investigated in a similar way. Because of the dependence of ω_o and the stability of equation 2 on J and C, it can be shown that for a given K, there exist many J and C values such that two eigenvalues of the system are always in the left half complex plane and $\Delta x(j\omega)/\Delta D(j\omega)$ remains arbitrarily close to 1/K for all $0<\omega<\omega_o$ [3]. If we consider C as a parameter that only guarantees a stable and slightly over-damped (or slightly under-damped) system, then we can claim that J is the only effective parameter in increasing or decreasing the frequency range of operation, ω_o, for a given K. Since a heavy system is always slower than a light system, a large target inertia, J, implies a slow system (narrow ω_o), while a small target inertia implies a fast system.

Parameterization of the set of performance specifications in

the case of more that one dimension is similar to the case when n=1. Matrix K in equation 2 models the first item of the set of performance specifications because the behavior of $[J s^2 + C s + K]$ approximates that of K for some bounded frequency range. The following is a summary of the parameterization of the set of performance specifications [3].

    Stiffness Matrix ---------------------------> K
    Frequency Range of Operation, ω_o ---------> J
    Stability ----------------------------------> C

By specifying the matrices J, C and K, a designer can modulate the impedance of the system. If a dynamic system is in contact with its environment and a new reference point is commanded (e.g., by a supervisor program), then, since the parameters of the impedance in equation 2 are under control, the resulting interaction load on the system will also be under control. This means that the controlled dynamic system will behave like a system that accepts a set of position and orientation commands and reflects a set of forces and torques as outputs. Impedance control can be contrasted with the two conventional modes of controlling a dynamic system: position control and force-control. Position control works well in unconstrained space, but causes difficulty when environmental constraints exist. In contrast, force control is desirable for manipulations in constrained space, but can result in bizarre motions when sufficient constraints are lacking. Position control and force control are two extreme cases of impedance control. The former implies very high impedance, while the latter implies very low impedance. Reference [3] presents a robust design method to achieve the target dynamics of equation 2 for a dynamic system.

Example [3]

Consider the case in which there is just one cable, C, between the vehicle, V, and a joint on a structure, S, in Figure 3. There is no constraint on the vehicle's motion in direction T; therefore, it is necessary to consider a closed-loop positioning system with a large stiffness for the vehicle along direction T. A large stiffness in direction T guarantees a good closed-loop positioning system in that direction. There is a constraint on the vehicle's motion in direction R because of the cable. Therefore it is necessary to consider a small stiffness for the control in direction R guaranteeing only a slight tension in the cable when the vehicle is commanded to move radially from unconstrained position (within the circle) to constrained position (on the circle.) Of course, once the vehicle's bow is moving on the circle, one can increase the stiffness in direction R to produce more tension. The frequency content of the commanded input implies a proper value for ω_o. Stiffness values in various directions, a suitable value for ω_o and the requirement of the stability imply proper values for K, J and C.
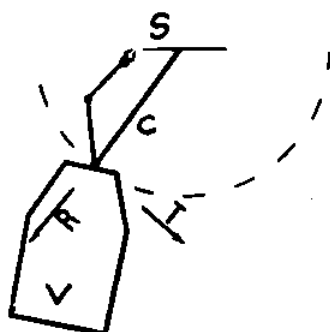
Figure 3: An Underwater Vehicle with one Cable

Simulation

Several dynamic/3D-graphic simulations of the constrained

maneuvers of underwater vehicles and manipulators were conducted to observe the quality of maneuvers in which impedance control and other controllers are employed [3]. The simulation consists of the dynamics of a six degree of freedom vehicle, cables (up to four), and environmental effects such as water drag. A 3D-graphic representation of the vehicle with cables is depicted on a vector display which is updated by the dynamic simulation at the rate of fifty hertz. The physical characteristics of a particular submersible vehicle called Recon 5 (Sea Grant I) are used as physical parameters in this simulation. This vehicle has five thrusters, weighs approximately 900 lbs., and is 6 feet long. The objective is to move the vehicle smoothly in direction X to gradually produce tension in the cable, without oscillation when the cable suddenly goes from being slack to being taut.
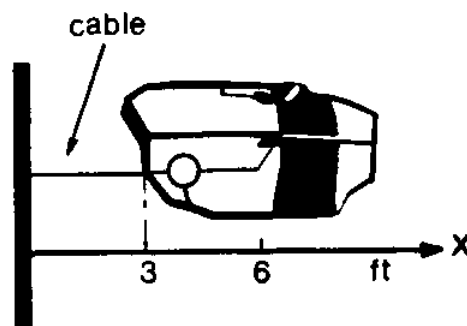

Figure 4: An Underwater Vehicle with One Cable

The time history of the command position in the X-direction is given in Figure 5. Plots b and c in Figure 5 show the cable tension and the vehicle position in direction X. The position reference inputs and the members of the K matrix are commanded continuously via analog signals to the computer. Here is the summary of a simple one-dimensional maneuver.

Region 1: In this region, the vehicle slowly approaches along direction X. The high feedback gain allows the vehicle to follow the reference input. There is no cable tension in this region. K is chosen to be 10 lbf/ft.
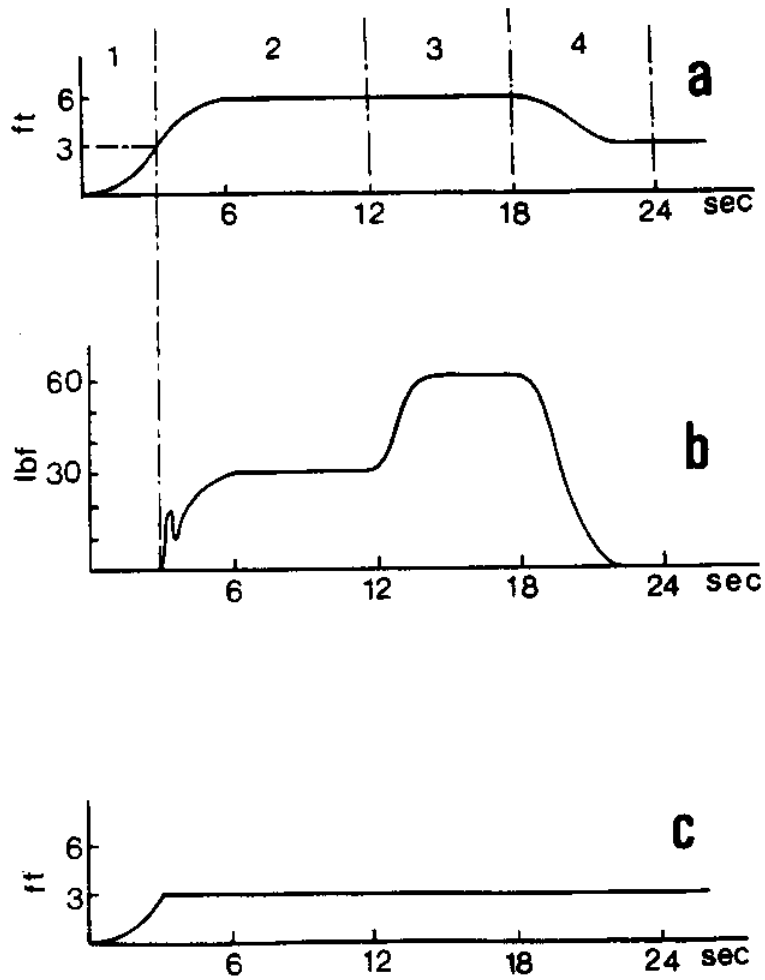
Figure 5: Time response of the vehicle motion.
a: Input Command   b: Cable Tension   C: Vehicle Position

Region 2: The vehicle encounters the cable. Since the cable is very stiff, a sudden tension occurs. An overshoot in the cable tension occurs because of the small velocity of approach of the vehicle at the moment of contact. The slower the vehicle approaches in direction X, the smaller the overshoot (at the very start of region 2) in the cable tension will be. If the vehicle hits the cable with the a large forward velocity and the reference input is not large, then the undershoot (right after the overshoot) of the cable tension might fall to zero. In other words the vehicle may bounce back a considerable distance. A similar situation occurs when a manipulator approaches a stiff wall. That is, if a manipulator hits the wall with a large forward velocity and the commanded position reference input is not significant, then the contact force might fall to zero and the end-point might separate from the wall. Since in this example the command position is three feet beyond the cable length at steady state, the cable tension is 30 lbf. Region 2 shows how the impedance control method allows for a relatively smooth transition period from the unconstrained to the constrained situation.

Region 3: In this region, K is increased from 10lbf/ft to 20 lbf/ft by an analog input to the computer while the reference input is kept constant. Since the command is kept constant, doubling K also doubles the cable tension; $\Delta D(j\omega) = K\Delta X(j\omega)$.
This region shows the significant capability that impedance control offers for monitoring the behavior of the vehicle at the interaction port. In this simulation, a human monitors the behavior of the vehicle by choosing the "right" K via an analog input signal to the computer. A computer can also be used to monitor K according to some "hidden logic". Having control of the impedance of the vehicle at the interaction port reveals the potential of using supervisory control [4] to monitor the vehicle behavior in complicated tasks.

Region 4: In this region, the input reference-position is

commanded to correspond to the cable length. This will give a zero cable tension in steady-state.

Conclusion

The work presented in this paper explains a theoretical method to develop wide-bandwidth position control for underwater and space vehicles. We suggested that the vehicles must be connected to environmental structures by means of cables or grabbers. This will develop large stiffness and wide bandwidth for the position control loop. The key issue is the notation of Impedance Control that allows for the control of the vehicles when they are connected to the environmental structures.

Acknowledgements

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